GOES-R Lithium-Ion Battery Life Test & Workhorse Battery Performance

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- Spacecraft, Electrical Power Subsystem Overview
- Battery Charge Control and State of Charge Profile
- Life Test Description
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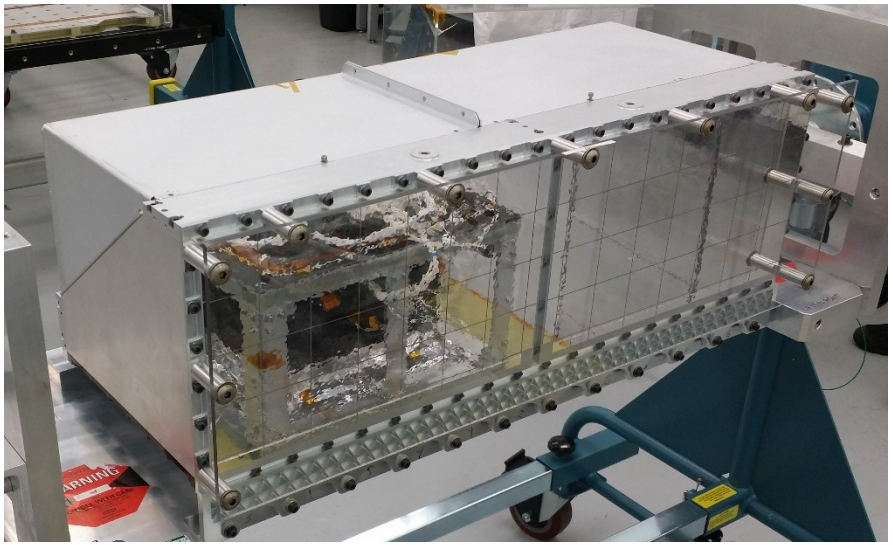
Overview

- **Lockheed Martin is under contract to NASA Goddard to design and build four GOES-R series satellites to be operated by NOAA.**
  - **GOES-R is the next-generation geostationary NOAA weather satellite**
  - **https://www.goes-r.gov/**
- **Saft's Space & Defense Division provides the VL48E cells and the GOES-R series lithium-ion batteries to Lockheed Martin.**
- **GOES-R series battery life testing is in process at Lockheed Martin.**
- **20 accelerated GEO seasons have been completed.**
  - **20 seasons represents 10 years of on-orbit operation.**
- **A GOES-R series qualification & I&T workhorse battery were built and supported spacecraft-level testing since 2014.**
- **The GOES-R series life test battery and workhorse batteries' performance will be presented.**

Life Test Battery Characteristics

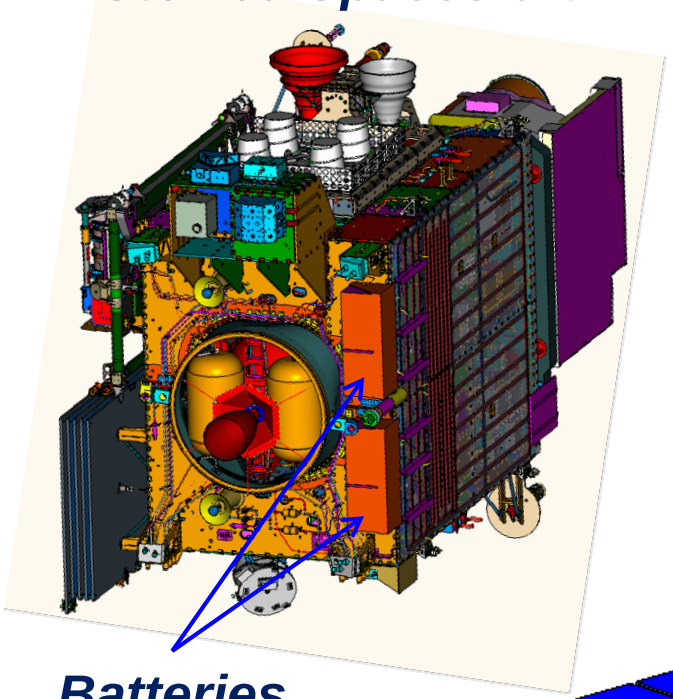
- Battery designed and manufactured by Saft in Cockeysville, Maryland.
- Life test battery built to flight drawings and processes.
  - Battery acceptance test performed 2014 Feb - Jun
- VL48E cells
  - Rated capacity (C_r) = 45.4 Ah at 20° C
    - C_r = required BOL capacity from 4.1 V to 3.0 V at C_n/2hr
  - Cells formed in 2011 Mar
- Electrical Configuration
  - 3 cells in parallel to form a cell bank
  - 12 cell banks in series to form a battery
  - Balancing circuits under FSW control apply current as needed to individual cell banks
  - Nameplate capacity (C_{bn}) = 113.5 Ah
    Rated capacity (C_{br}) = 136.2 Ah at 20° C
- Mechanical configuration
  - 3 cells in a module; 12 modules in a battery
  - Thermistors, heaters, and radiator for thermal control
  - Isolated aluminum housing to protect against shorts and to enclose possible cell failures



Fully Assembled Battery
(with non-flight radiator shield attached)

Battery Locations

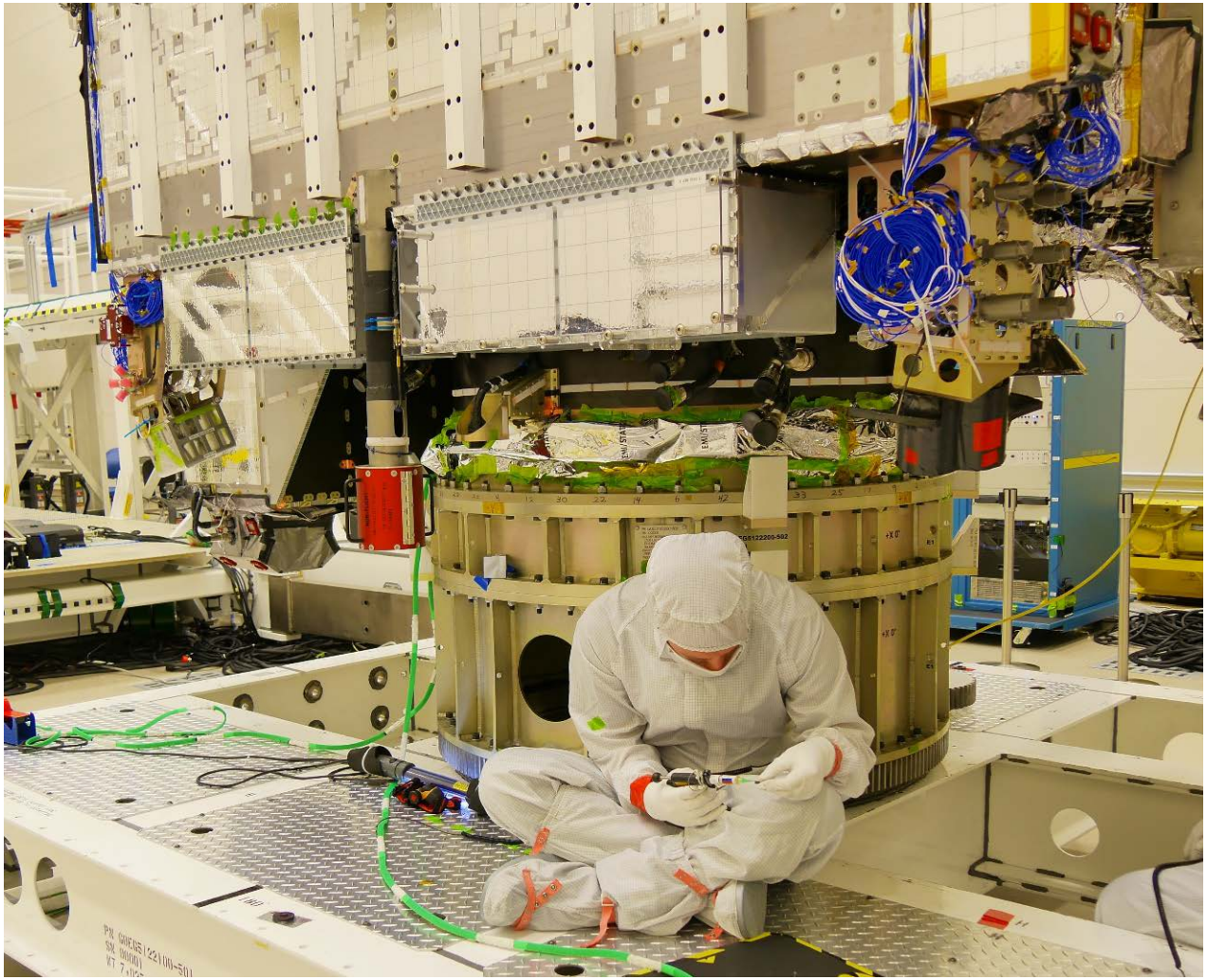
Stowed Spacecraft



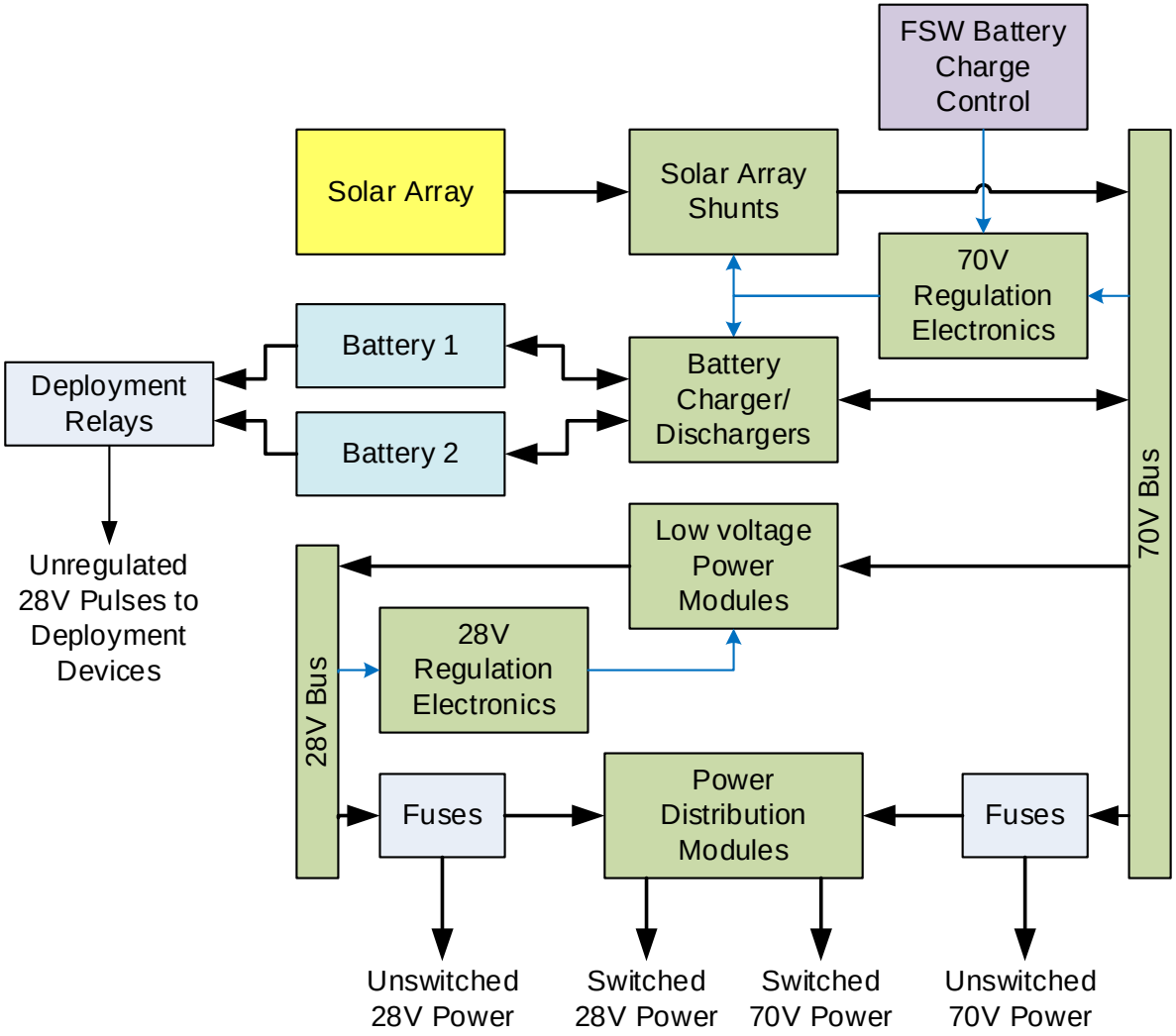
Batteries

Fully Deployed Spacecraft

Battery Installed on Spacecraft

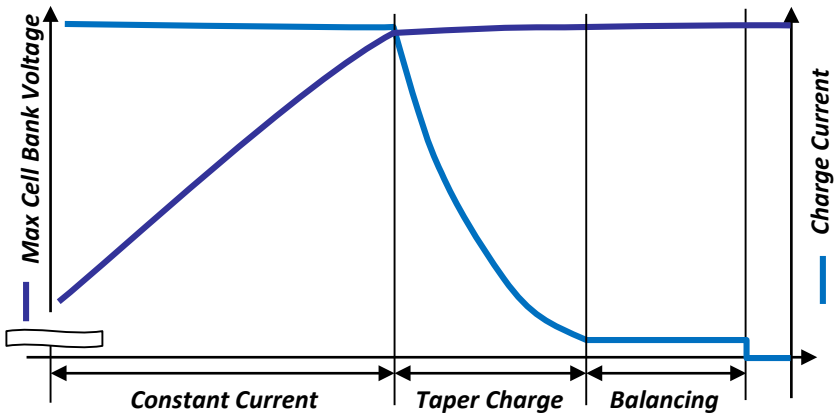


Electrical Power Subsystem Diagram



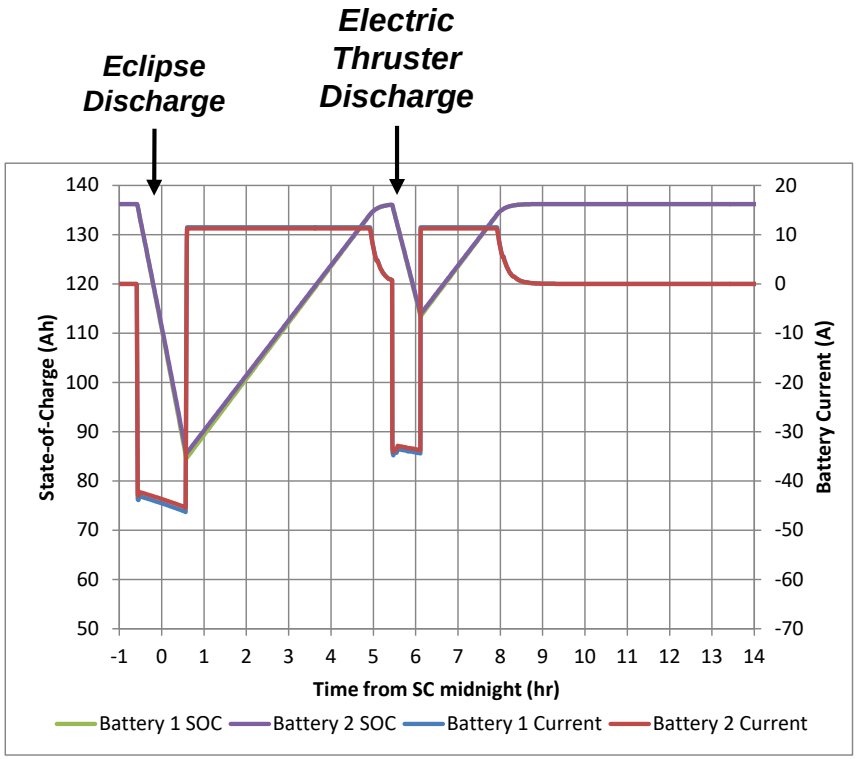
Battery Charge Control and SOC Profile

Charge Control



- ***Charge control uses a constant current/constant voltage approach***
  - ***Constant current at C_{br}/13hr until cell voltage reaches end-of-charge set point***
  - ***Constant voltage (taper charge) until current drops to approx. C_{br}/210hr***
- ***Balancing performed at end of recharge; current = C_{br}/210hr***

State-of-Charge Profile



Life Test Description

- Flight-like charge control and balancing
- Real-time eclipse season cycling
  - Eclipse season is 44 days; Eclipse discharge once per day
  - Eclipse duration varies over the season from a few minutes to 70 minutes
  - Average eclipse discharge current for longest eclipse = 73 A
  - Max eclipse discharge = 75% C_{bn} (85 Ah out)
  - Electric thruster discharge once every four days, DOD = 36% C_{bn} (41 Ah out)
  - Average electric thruster discharge current = 28 A
- Accelerated solstice season cycling
  - Accelerated solstice season is 11 to 17 days
  - Two electric thruster discharges per day, DOD = 36% C_{bn} (41 Ah out)
  - Average electric thruster discharge current = 28 A
- End-of-charge voltage (EOCV) increased over life
  - BOL is 3.95 V/cell bank, EOL is 4.05 V/cell bank
- Battery environment held at 15°C throughout test

Life Test Capacity and Impedance Results

Test Condition*	Capacity (Ah) †	Cell Impedance (mΩ) ‡
Final acceptance test at Saft	136.22	3.25
Baseline just before life test cycling began	139.87	3.13
After 4 eclipse/solstice seasons	138.96	3.29
After 10 eclipse/solstice seasons	140.31	3.58
After 20 eclipse/solstice seasons	141.80	3.89

* Capacity tests at LM used same special test equipment that is used for life test

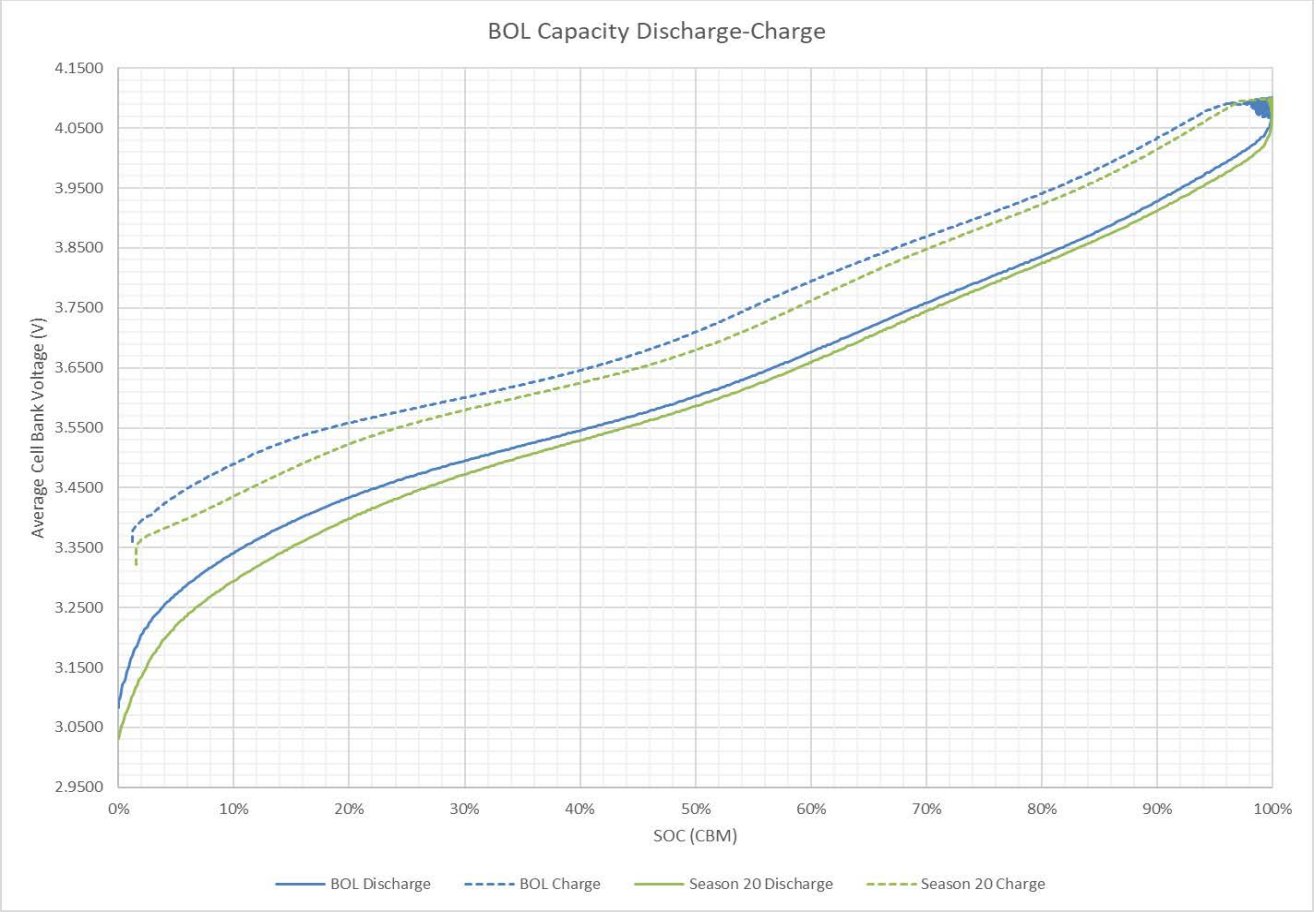
† Measured *from 4.1 V to 3.0 V at C_{bn}/2hr*

Increased capacity likely due to test equipment/measurement variations

‡ Average cell impedance (ohmic and polarized) at start of capacity discharge

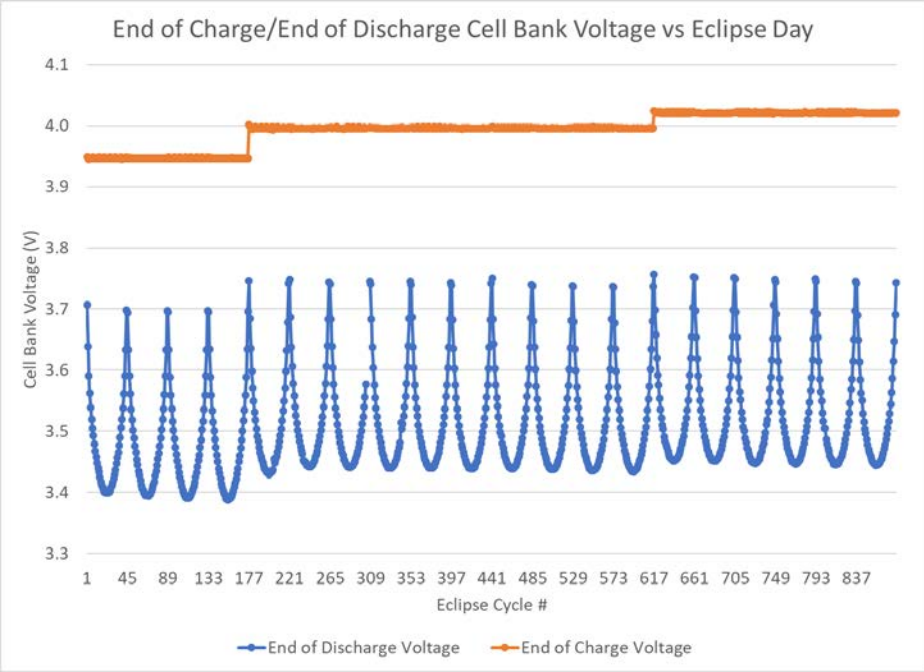
No Discernable Change in Capacity After 20 Seasons

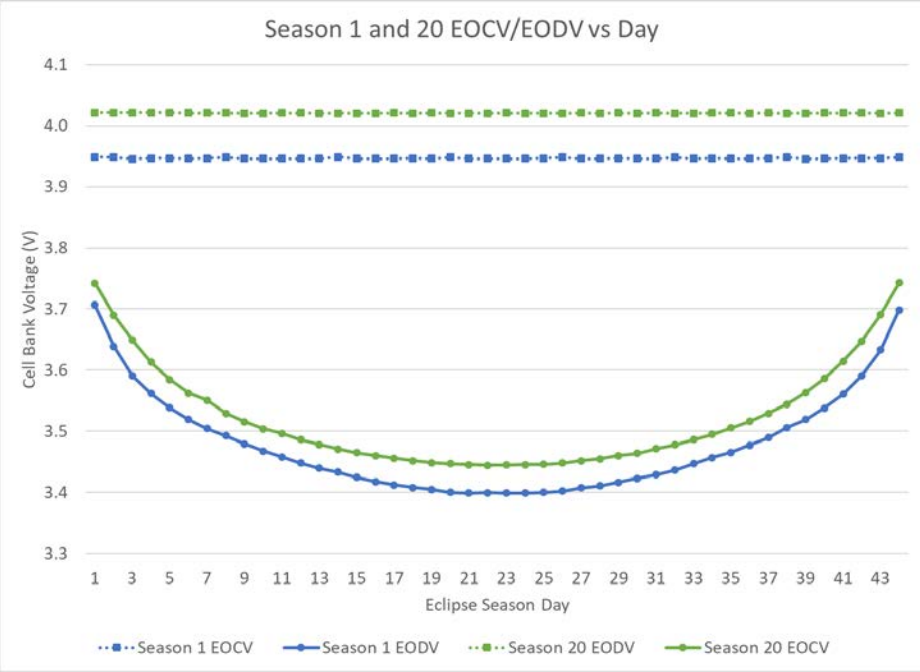
Charge/Discharge Voltage



Voltage fade due to impedance increase

Max/Min Cell Bank Voltage





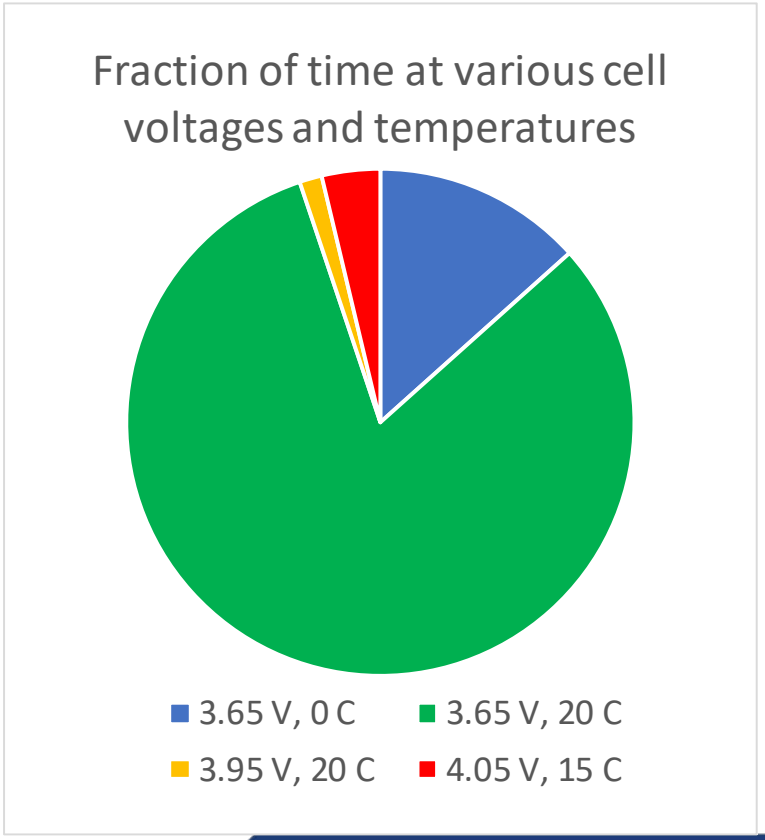
EOCV increases negate voltage fade

Workhorse Battery Characteristics

- Used in spacecraft testing from 2014 April to present.
  - Flight batteries installed shortly before spacecraft ships to launch site
- Cells formed in 2011 March, same lot as life test battery.
- One battery was exposed to proto-flight testing.
  - Higher vibration level and more extreme thermal cycling than acceptance
  - Testing perform from 2013 November to 2014 April
- Other battery was exposed to qualification testing.
  - Higher vibration level and more extreme thermal cycling than proto-flight
  - Testing perform from 2013 August to 2014 January
- Capacity test performed in 2018 February, 7 years after cell formation.

Workhorse Battery Utilization and Capacity

Workhorse Battery Utilization



Work-Horse Battery Performance

- **Workhorse cells formed in March 2011.**
- **Average cell acceptance 20 °C Capacity: 45.64 Ah**
  - **Cell acceptance testing 6-2011 – 12-2011**
- **Qual Battery 20 °C Capacity:**
  - **Expected after cell testing: 137.2 Ah**
  - **January 2014: 138.2 Ah**
  - **February 2018: 140.3 Ah**
- **I&T Battery 20 °C Capacity**
  - **Expected after cell testing: 136.7 Ah**
  - **March 2014: 136.5 Ah**
  - **February 2018: 138.2 Ah**

No capacity loss after 6.5 years

VL48E Cell Chemistry Performance

- **Capacity increase expected during early seasons.**
  - **Due to soaking of electrolyte into electrode, and repartition of binder on positive electrode.**
- **Capacity is expected to fade by season 20 – observed increase likely due to measurement accuracy.**
  - **15-year capacity fade should be less than 1%.**
- **Discharge voltage is decreasing as expected due to impedance increase over life.**
- **Expected energy decay is 5% to 6% after 15-year mission.**
  - **Depends on battery storage voltage & charge voltage at solstice/eclipse.**
  - **Anode/electrolyte designed for negligible SEI decay during 15-year GEO mission.**
  - **Cathode formulized to minimize the cathode capacity fade, by providing a good electric conduction network and protected NCA particle surface.**

Conclusions

- **GOES-R Series Lithium-Ion Life Test Battery Results**
  - Accelerated GEO testing: 20 seasons of 30 complete
    - Real-time eclipse seasons of 44 days each.
    - Maximum eclipses at 75% DOD of C_{bn}(113.5 Ah).
    - Accelerated solstice seasons of 11-17 days.
  - No degradation in 20 °C capacity after 20 seasons of accelerated GEO
    - BOL 20 °C Capacity: 139.9 Ah
    - 20-season accelerated GEO 20 °C capacity: 141.8 Ah
    - 1.36% delta due to test equipment accuracy and temperature control.
- **GOES-R Series Work-Horse Battery Performance**
  - No degradation in 20 °C capacity 6.5 years after cell acceptance testing.
    - Four years of ground operations at ambient.
    - Majority of time (~80%) at 3.60 V – 3.65 V and 20 °C.
    - Remaining time at 3.65 V and 0 °C or 3.95 V – 4.05 V and 15 °C – 20 °C.
- **Batteries/Cells Are Performing as Expected – No Concerns with Meeting 15-year Mission Life**

Appendix: Acronym List

C_{bn}: Battery nameplate capacity. The battery nameplate capacity, C_{bn}, is 5/6 of the battery rated capacity, C_{br}. The battery nameplate capacity, C_{bn}, is the minimum capacity at 20 °C when the battery cells are charged to 4.1 V and discharged with a $C_{bn}/2$ discharge rate to 3.0 V which the battery manufacturer guarantees for the mission life. The term, C_{bn}, is, also, a current which is numerically equivalent to the nameplate capacity, Ah, and is used to define the charge current or discharge current during capacity measurements. Therefore, a battery nameplate capacity, C_{bn}, at 120 Ah with a discharge rate of $C_{bn}/2$ would be discharged at 120 A/2 or 60 A during the capacity measurement. For GOES R, the battery nameplate capacity, C_{bn}, is 113.5 Ah.

C_{br}: Battery rated capacity. The battery rated capacity, C_{br}, is the battery capacity requirement which the spacecraft manufacturer agrees to meet prior to build. The battery rated capacity, C_{br}, is the beginning-of-life (BOL) capacity at 20 °C when the battery cells are charged to 4.1 V and discharged with a $C_{bn}/2$ discharge rate until the 1st battery cell end-of-discharge voltage is 3.0 V. For GOES R, the battery rated capacity, C_{br}, is 136.2 Ah.

Appendix: Acronym List

C_n: Battery cell nameplate capacity. The battery cell nameplate capacity, C_n, is 5/6 of the battery cell rated capacity, C_r. The battery cell nameplate capacity, C_n, is the minimum capacity at 20 °C when the cell is charged to 4.1 V and discharged with a $C_n/2$ discharge rate to 3.0 V which the cell manufacturer guarantees for the mission life. The term, C_n, is, also, a current which is numerically equivalent to the nameplate capacity, Ah, and is used to define the charge current or discharge current during capacity measurements. Therefore, a battery cell nameplate capacity, C_n, at 40 Ah with a discharge rate of $C_n/2$ would be discharged at 40 A/2 or 20 A during the capacity measurement. For GOES R, the C_n was 37.83 Ah.

C_r: Battery cell rated capacity. The battery cell rated capacity is the battery cell capacity requirement which the cell manufacturer agrees to meet prior to build. The battery cell's rated capacity, C_r, is the beginning-of-life (BOL) capacity at 20 °C when the cell is charged to 4.1 V and discharged with a $C_n/2$ discharge rate to 3.0 V. For GOES R, the VL48E battery cell rated capacity was 45.4 Ah.

Appendix: Acronym List

GOES: Geostationary Operational Environmental Satellite

NASA: National Aeronautics and Space Administration

NCA: Lithium nickel cobalt aluminum oxide ($LiNiCoAlO_2$)

NOAA: National Oceanic and Atmospheric Administration